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Characterization of Tritium Breeding Ratio and Energy Multiplication Factor of Lithium-based Ternary Alloys in IFE Blankets

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Abstract— Lawrence Livermore National Laboratory (LLNL) developed an inertial fusion energy (IFE) chamber concept that uses liquid lithium as the tritium breeder and primary coolant. *Lithium metal has multiple benefits including high tritium breeding capability and excellent heat transfer properties. Nevertheless, lithium highly reacts with air and water to create an alkali metal fire. As a result, LLNL is now conducting research and development to identify lithium-based ternary alloys that will keep the favorable attributes of lithium while reducing the chemical reactivity and fire hazards. 3-D Monte Carlo calculations of a simplified model of the laser IFE reactor were performed for the assessment of two characteristics: tritium breeding ratio (TBR) that is the ratio of tritium produced in the system to tritium consumed, and the fusion energy multiplication factor (EMF) that is the ratio of the total power deposited in the blanket and other regions outside the IFE chamber by neutrons, gammas, and alpha particles to the fusion power. The TBR and EMF were calculated for each ternary combination as a function of the alloy composition varying the atomic percent of each element in the mixture from 0 to 100% by increments of 5%. Mixtures that guarantee a TBR of at least 1.02 and an EMF of at least 1.10 were considered viable. It was found that (1) alloys containing bismuth or lead offer the wider range of acceptable compositions; (2) ternary alloys made of lithium, with either lead or bismuth, and a third element of zinc, strontium, barium, or copper can reduce the lithium concentration below 20%. In evaluating the overall performance of the blanket coolant, it is important to maintain the lithium concentration at a minimum to reduce chemical reactivity in lithium.*

Keywords—IFE; lithium; ternary; tritium breeding ratio; energy multiplication factor

I. Introduction

The LLNL laser IFE concept is based on an indirect-driven target composed of deuterium-tritium fuel [1]. The fusion driver/target design implements the same physics currently experimented at the National Ignition Facility (NIF). Lithium is highly regarded to act as both a breeder and coolant in the fusion chamber blanket. Pure liquid lithium has many attributes and benefits including prevailing heat transfer, low pressure, and low activation. Additionally, it has very high tritium solubility and thus, the tritium permeation levels are very low [1]. Nevertheless, lithium metal can chemically react with both water and air, produce hydrogen, and create an explosion hazard on the plant [2]. The goal of Lawrence Livermore National Laboratory (LLNL) is to find a lithium-based alloy that reduces the fire hazards while retaining the attractive characteristics of pure lithium. This study examines some of the neutronics for a variety of lithium-based ternary alloys.

II. Methodology

A. Chamber Model

The chamber is modeled as a spherical chamber with a 13m innermost region and target in the center. The D(T,n)α reactions in the ICF target releases 132 MJ with 97.45 MJ from the neutrons and the rest from x-rays and ions [3]. Neutrons emitted by the deuterium-tritium (DT) reactions are subsequently absorbed by both the DT target and lead hohlraum. This creates (n,2n) reactions leading to an increase in the number of neutrons leaving the hohlraum by 2.8%. The alpha particles are also absorbed in the compressed DT fuel and lead hohlraum to produce x-rays and ions [4]. This outgoing x-rays and ions are attenuated by a background xenon gas at a density of 6 $\mu g/cm^3$ before they can reach the first wall. TABLE I outlines the layers of steel structure and coolant/breeder that surround the central region. HT9 steel is chosen for the first wall and blanket structure due to its high resistance against radiation damage and low chemical reactivity; the coolant/breeder blanket is comprised of a lithium ternary alloy. The outermost region is made up of 1m of graphite.

TABLE I. COMPOSITIONS AND DIMENSIONS OF THE BLANKET

Layer, #	Material	Thickness (cm)
1	HT9	0.5
2	Breeder/Coolant	1
3	HT9	0.5
4	Breeder/Coolant	100
5	HT9	0.5
6	Breeder/Coolant	50
7	HT9	0.5
8	Graphite	100

B. Neutron and Photon Transport

Monte Carlo transport code MCNP6 was used for neutron and transport calculations [5] with the model illustrated in Fig. 1. Due to the complexity of the DT target, a point source containing a neutron energy distribution outlined in Figure 2 was used instead. The energy spectrum in Fig. 2 accounts for the scattering reactions of the fusion neutrons with the DT target and lead hohlraum. ENDF/B-VII.I cross sections at 900 K were provided for all of the materials in the model [6].

Two main neutronics performance characteristics were calculated for the blanket: tritium breeding ratio (TBR), and the energy multiplication factor (EMF). The TBR is defined as the ratio of tritium produced in the blanket to the tritium consumed in the target [7].The TBR must be greater than unity for the system to be self-sufficient and account for losses in the design including the first wall, blanket structure, penetrations, and decay after extraction. The minimum TBR constraint used in LLNL study was 1.02; this is lower than what other fusion plants demand due to the high fractional burn-up in the IFE source and lower tritium permeation in the coolant [8]. The EMF is defined as the ratio of power deposited in the blanket and other regions outside the LIFE chamber by neutrons, gammas, and alpha particles to the power derived from fusion reactions [9]. It is given by:

$$EMF = (E_d + E_\alpha) / 17.6 \qquad (1)$$

where E_d is the total energy deposited in the chamber (first wall, breeding regions, structures, and reflector) and surrounding regions (shield, beam dumps, etc) as the result of neutron and secondary gamma reactions. E_α is the energy of the x-rays and ions absorbed in the chamber gas (4.026 MeV). The denominator represents the total fusion energy released per D-T reaction. The power from the neutron and neutron induced gamma energy deposited in regions outside the chamber is expected to be recovered and is therefore included in the numerator of (1). The goal is to maximize the EMF in order to lower the cost of electricity from the fusion power plant without putting an unreasonable demand on power production. For this preliminary study, the EMF chosen is 1.1.

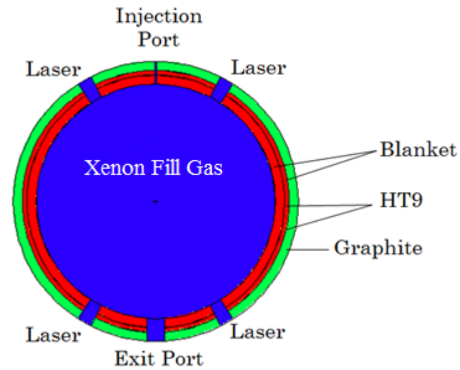


Fig. 1. MCNP model of LIFE viewed from the xz plane.

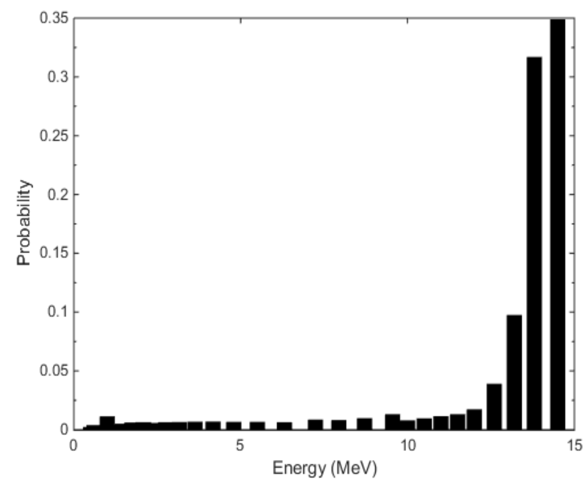


Fig. 2. Neutron point source energy spectrum

III. RESULTS

A. Sweep of Ternary Alloys

A subset of elements to analyze was provided by LLNL based on thermodynamics properties (sodium, magnesium, aluminum, silicon, calcium, titanium, copper, zinc, gallium, strontium, palladium, silver, indium, tin, antimony, barium, gold, lead, and bismuth). Over 60 combinations were analyzed. TBR and EMF were calculated as a function of alloy composition varying the amount of each element in the mixture from 0% to 100% by increments of 5%. Results containing the range of lithium concentrations for various ternary alloys that meet the TBR constrain of 1.02 and EMF goal of 1.1 are outlined in Fig. 3.

The alloys that met the TBR and EMF criteria with the widest range of lithium concentrations did so with the lowest amount of lithium. It is important to account for the minimum amount of lithium that meets the criteria to lower the chemical reactivity of the alloy. It can be seen, in Fig. 3, that when the range of acceptable lithium concentrations decreases, in most alloys, the minimum amount of lithium that meets the criteria increases. The alloys with the widest ranges of lithium concentrations and minimum lithium fraction, below 20%, are those containing elements such as barium, bismuth, lead, strontium, zinc, and copper. Specifically, a combination of bismuth or lead with lithium and a third element had the best results. Lead and bismuth are next to each other on the periodic table and have many similar properties including a high neutron (n,xn) cross section. This enhances tritium breeding in the blanket. Additionally, ternaries with either of these two elements and sodium met the TBR and EMF criteria at 5% lithium, the lowest concentration in all the alloys. It is predicted that a low absorption cross section in sodium can help increase the TBR at low lithium concentrations in alloys with lead and bismuth.

B. LiPbBa

Ternary graphs for one of the best cases, LiPbBa are shown in Fig. 4. The TBR in Fig. 4(a) ranges from 0 to 1.6; this provides a wide spectrum of concentrations in case the minimum TBR constrain needs to be raised due to additional uncertainties in the design. The EMF range is narrower with a maximum at around 1.35. However, LiPbBa is able to meet the EMF design goal for the majority of ternary compositions. Fig. 5 illustrates the information in Fig. 3 but in a ternary plot for LiPbBa with the shaded region indicating the acceptable concentrations of each element that meet the TBR and EMF criteria. The TBR dictates the concentrations of lead and barium that are able to meet the 1.02 limit for a given lithium concentration. At low lithium concentrations, there are lower amounts of barium; as the amount of lithium increases, so does barium. The amount of barium reaches a maximum close to 50% lithium and begins to decrease again to compensate for the higher amounts of lithium.

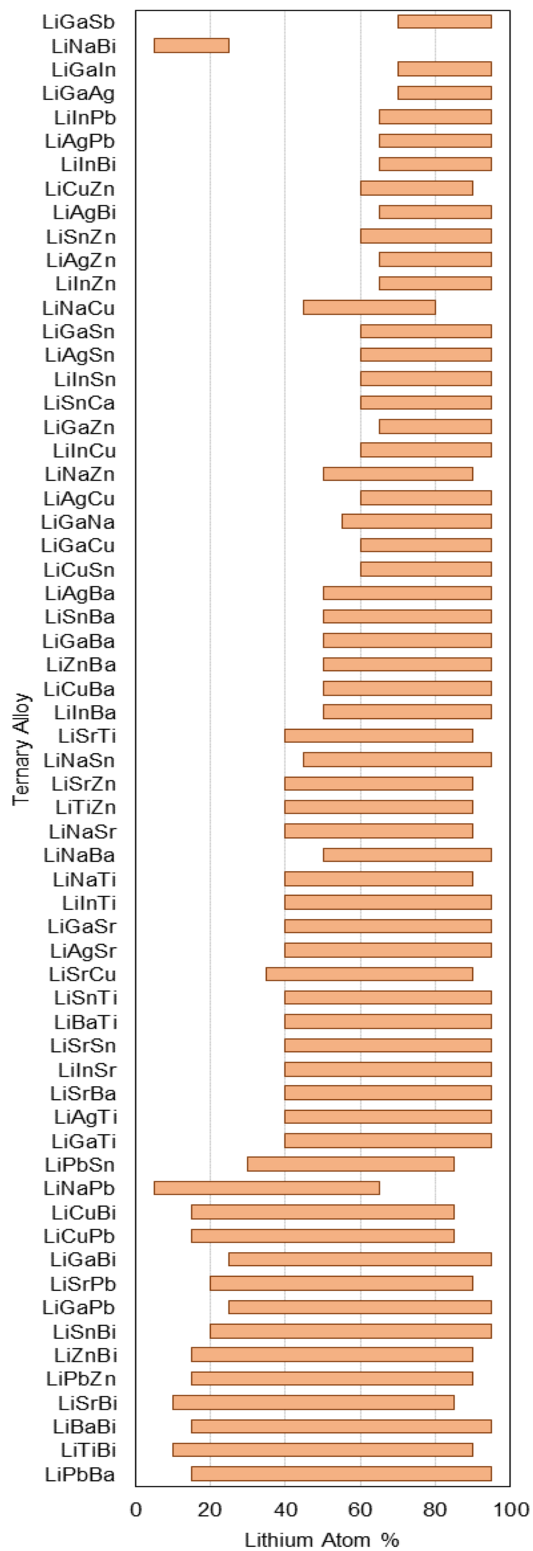
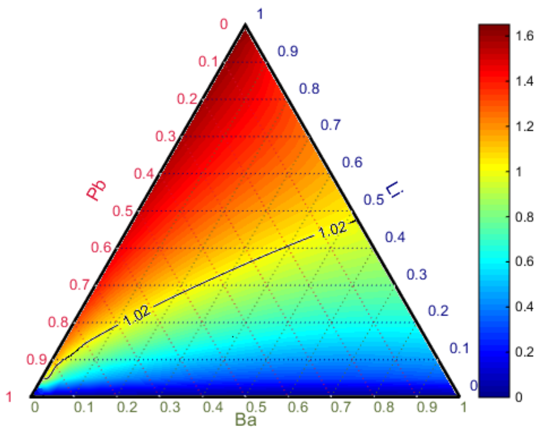
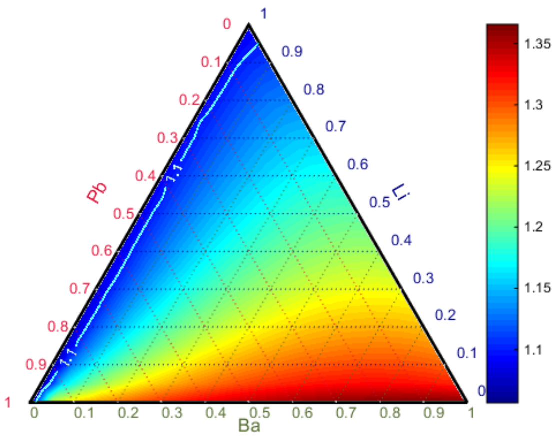


Fig. 3. Summary of lithium ranges for ternaries that meet TBR $\geq$ 1.02 and EMF $\geq$ 1.1



(a)



(b)

Fig. 4. TBR (a) and EMF (b) for LiPbBa alloys as a function of composition

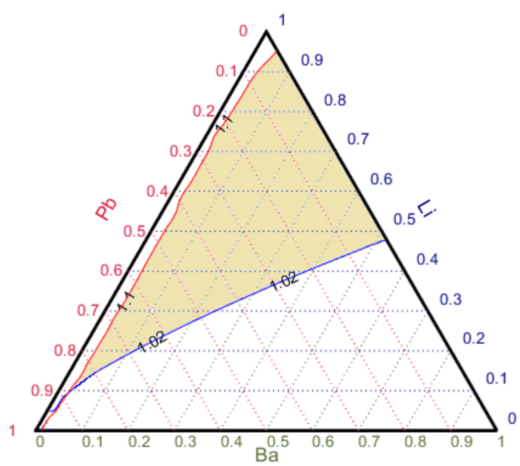
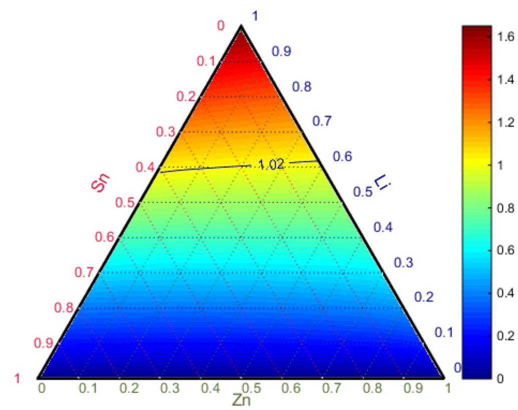


Fig. 5. Acceptable domain of LiPbBa compositions

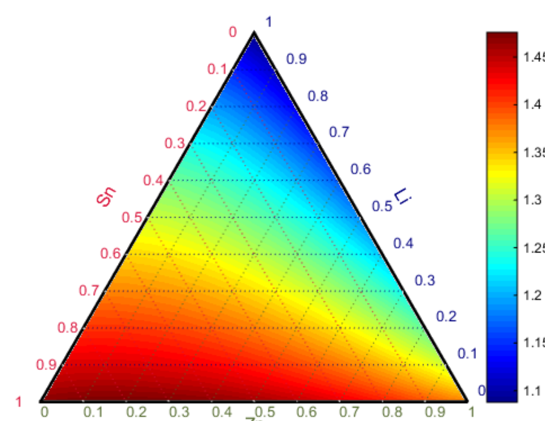
C. LiSnZn

Another alloy closely studied is LiSnZn. This alloy demonstrated an adequate range of acceptable lithium concentrations in Fig. 3, although it was not one of the best. However, zinc and tin both have high heat transfer coefficients making this alloy attractive as an overall candidate. The range of TBRs in Fig. 6(a) is similar to LiPbBa; nevertheless, the minimum amount of lithium that meets a TBR of 1.02 is much higher at around 60%. This is due to tin and zinc lacking the neutron multiplication reactions that are found in lead. Additionally, tin and zinc maximize the EMF in Fig. 6(b) with them being greater than or equal to the design goal. Consequently the minimum lithium concentration that meets the parameters is limited by the TBR (Fig. 7).

Among the acceptable cases, a composition of 70% lithium, 20% tin, and 10% zinc was chosen for further analysis. The neutron spectrum in different regions of the system is illustrated in Fig. 8. A dip is observed in every region around 0.4 MeV due to absorption found in ^{6}Li. TABLE II gives a detailed breakdown of the contributions to the tritium breeding ratio by blanket region and type of reaction for the same case. As expected, the majority of the breeding occurs in the 100cm thick layer. On a per volume basis (the last column on the table), the innermost layer is the most effective due to the high neutron energy reactions with ^{7}Li in addition to the reactions with ^{6}Li. As the neutrons travel outward, they slow down and tritium production becomes dominant in ^{6}Li; it is most prominent in layer 6 (adjacent to the reflector). Future work will take a look at ^{6}Li enrichment to enhance the TBR.



(a)



(b)

Fig. 6. TBR (a) and EMF (b) for LiSnZn alloys as a function of composition

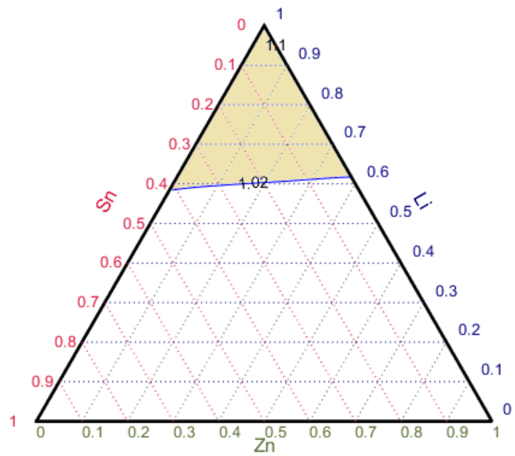


Fig. 7. Acceptable domain of LiSnZn compositions

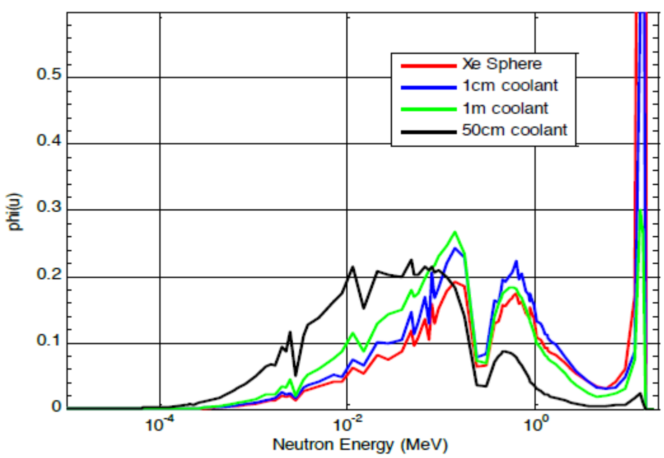


Fig. 8. Nuetron spectrum at different blanket positions for LiSnZn.

TABLE II. CONTRIBUTIONS TO TBR FROM ^{6}LI AND ^{7}LI IN THE THREE BREEDER/COOLANT LAYERS

Layer	Volume (m^3)	Volume Fraction (VF)	T6[a]	T7[b]	Layer TBR = T6 + T7	TBR/ VF
2	5.33	0.0053	0.0142	0.0082	0.0223	4.21
4	620.68	0.6167	0.8054	0.2190	1.024	1.66
6	380.15	0.3778	0.0928	0.0024	0.0952	0.25
TOTAL	1006.15	1.00	0.9123	0.230	1.142	1.14

a. T6 = ^{6}Li(n,T) reactions per DT fusion

b. T7 = ^{7}Li(n,n'T) reactions per DT fusion

IV. CONCLUSIONS

The preliminary analysis in this paper examines a series of ternary alloy that could potentially be utilized as a dual coolant and breeder blanket for the laser IFE power plant. Transport analyses of ternary systems were tested with MCNP. Alloys that had the widest range of acceptable lithium concentrations for a TBR constrain of 1.02 and EMF design goal of 1.1 also met both criteria with some of the lowest amounts of lithium. These included ternaries composed of lithium, lead or bismuth, and a third component. Both TBR and EMF were enhanced in LiPbBa, and thus, it showed one of the best overall results. On the other hand, tin and zinc in LiSnZn boosted EMF, and consequently compromised TBR; these elements do not multiply neutrons as effectively as lead or bismuth. Future studies will look at the cross sections of elements to determine what characteristics aid the optimization of both TBR and EMF. When the contributions of ^{6}Li and ^{7}Li to the TBR were compared, ^{6}Li was dominant in all three layers of the blanket. This means that increasing the ratio of ^{6}Li to ^{7}Li will enhance the TBR. Later studies will look at lithium enrichment to see if this lowers the minimum total lithium concentration in the alloy. Reducing the amount of lithium is important to prevent fire hazards from chemical reactions in the blanket.

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